1 Introduction

Carbon nanotube (CNT) [1–3], either as a model system for the broad study of properties in low dimensionality or as a unique object having excellent mechanical and electronic properties, has played a central role in leading the overall progress of nanoscale science and technology in the last decade. Nanoscale transistor [4–6], electromechanical actuator [7,8], biomolecular and chemical sensor [9,10], and high resolution probe [11,12] have been developed with CNT in the device fabrication level, as well as reinforcement nanocomposite [13–21] and field emission array in the commercial production level [22–26]. Such versatile applications stem essentially from the novel structure of CNT. CNT can be geometrically described as a seamless cylinder of a rolled graphene sheet (called a single wall CNT), or multiple nested cylinders consisting of rolled graphene sheets (called a multiwalled CNT). Depending on the rolling direction, a CNT can be expected to possess different lattice symmetry (chiral symmetry). It is the combination of the chiral symmetry and the unique properties of graphene that ultimately determine many unprecedented mechanical and electronic properties of CNT [27]. For example, CNT has been modeled [28] and measured as having the highest tensile yield strength, as high as 170 GPa, among existing materials; CNT can either be metallic and semiconducting depending on its chiral symmetry and due to quantum confinement effect; Single wall CNT (SWCNT) has been demonstrated to be a ballistic conductor even at room temperature, where electrons propagate through the CNT with the absence of effective scattering over several hundreds nanometers [29]; and the electronic and chemical properties of CNT can be effectively modulated by the local structural deformation of CNT [30,31]. With the rapid progress in the synthesis of large quantity and high quality CNTs [32–35], many researchers have also begun to focus on the manufacturing and engineering of CNTs for developing new composite materials and electronic products. Some notable examples include the development of nanotube-reinforced fiber and composite materials (including polymer, metal and ceramic composites) [17–21] and large scale CNT field emission array for flat panel display [24–26]. In such development, results have shown that a small percentage addition of CNT can dramatically improve the mechanical, electrical and thermal properties of polymer composite; and the nanometer-size, large aspect ratio and the high electrical/thermal conductivity of CNT allow a CNT field emission array to be operated at very low threshold voltage and with very small power consumption.

The rapid advance of CNT-related research in many fronts can not obviously be captured by a few examples above. In the following, I attempt to focus this review on the mechanical properties of CNT and the experimental methods for the characterization of such properties.

2 Mechanical Properties of CNT

The basic mechanical properties of CNT can be understood from knowing the basic properties of a graphene sheet. Carbon atoms in a graphene sheet are arranged in a planar hexagonal lattice structure, with each carbon atom covalently bonded with three nearest carbon atoms. Within the plane, three of the four C-C bonds are strong p bonds. In forming graphite, the graphene sheet is stacked with the three nearest carbon atoms. With the rapid progress in the synthesis of large quantity and high quality CNTs, many researchers have also begun to focus on the manufacture and engineering of CNTs for developing new composite materials and electronic products. Some notable examples include the development of nanotube-reinforced fiber and composite materials (including polymer, metal and ceramic composites) [17–21] and large scale CNT field emission array for flat panel display [24–26]. In such development, results have shown that a small percentage addition of CNT can dramatically improve the mechanical, electrical and thermal properties of polymer composite; and the nanometer-size, large aspect ratio and the high electrical/thermal conductivity of CNT allow a CNT field emission array to be operated at very low threshold voltage and with very small power consumption.

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has a shear strength value in the range of 0.48 MPa [36]. Ruoff et al. [37] indeed derived, in their earlier studies, the mechanical and thermal properties of CNT based on the known properties of graphite and the general scaling law in mechanics, and highlighted the importance of the interface mechanics between CNT and matrix for making high strength CNT-reinforced composites. Such a derivation, though oversimplified, provided actually very sound estimates of many properties of CNT, especially for large diameter CNTs.

2.1 The Young’s Modulus of CNT. Early theoretical studies of the Young’s modulus of CNT were mostly based on first principle calculations and molecular dynamics. Overney et al. [38] in 1993 first calculated the rigidity of (5, 5) CNTs from first principles, which gave an estimate of the Young’s modulus between 1.5 TPa and 5.0 TPa. Yakobson examined, from the perspective of the classic continuum shell model, the result calculated based on molecular dynamics, and obtained a Young’s modulus of 5.5 TPa by assigning an effective shell thickness of 0.066 nm for CNT [39]. Lu carried out extensive studies of the elastic properties of CNT using molecular dynamics and deduced a Young’s modulus of 1 TPa [40,41]. More recently, various groups [42–50] have developed atomic scale continuum methods (multi-scale model) to more efficiently model the elastic properties of CNT with large dimension and complex structure. The Young’s modulus of the CNT obtained with such new methods falls also in the range of 1 TPa. In general, the Young’s modulus of CNT is insensitive to its chirality and diameter according to the modeling.

Owing to the small dimension of individual CNTs, the direct experimental measurement of the Young’s modulus of CNT is not trivial. Treacy et al. [51] carried out the first successful measurement of the Young’s modulus of individual MWCNTs by thermally inducing the vibration of cantilevered MWCNTs in transmission electron microscope (TEM). By measuring the dependence of the vibration amplitude on temperature, and by assuming the validity of the classic beam vibration model for the MWCNT, the Young’s modulus was measured to be in the range of 0.4 to 4.15 TPa (mean value 1.8 TPa). Krishnan et al. [52] applied the same method for measuring the Young’s modulus of SWCNT having diameters around 1 nm and lengths ~30 nm. The averaged Young’s modulus value obtained from the measurement of 27 SWCNTs was 1.3 TPa. In a thermally excited vibration, every resonance modes of the cantilevered CNT provide weighted contributions to the resulting vibration according to the equipartition theorem for energy. Such a beam oscillation based technique was dramatically improved by Poncharal et al. who developed an electric-field induced resonance method to directly induce the mechanical resonance of selected harmonic modes in MWCNT [53].

In the experiment, a retrofitted TEM sample holder integrated with a piezoelectric tube for fine nanomanipulation was developed. The developed tool allowed the positioning of a manipulation probe, usually a conductive probe, within the close proximity from the selected MWCNT candidate for inducing its mechanical resonance with an applied oscillating electric field. The method also allowed the structure of the MWCNTs to be studied in situ with high resolution. The measured Young’s modulus values for MWCNTs, calculated based on treating MWCNT as a cantilevered simple beam, ranged from 0.1 TPa to 1 TPa; and were found to be dependent on their diameters. The modulus decreased rapidly with the increase of diameter in the span of 12 nm to 42 nm as shown in Fig. 1. Such dependence was interpreted as the result of the ripple formation in the bending deformation during the oscillation of MWCNT. For thick-walled and large diameter CNT, experiments and theoretical modeling have indeed found that a ripple-like deformation tends to form in the compressed side of a bent CNT, which could, in principle, introduce nonlinear effect in the resonance response of CNT, and invalidate the oversimplified beam mechanics theory used for estimating the Young’s modulus of the MWCNT from the resonance frequency [45,54–56]. The Young’s modulus measured from such a resonance method is thus better termed as an effective bending modulus. Static beam deflection method was also implemented to measure the bending modulus of MWCNT. Wong et al. [57] used lateral force microscopy to measure the dependence of the deflection of a cantilevered MWCNT on the lateral force applied by a probe. The MWCNT was placed on a low friction MoS₂ substrate and pinned at one end by a deposited SiO pad. The bending modulus of MWCNT estimated from the measurement is 1.28±0.59 TPa. Salvetat et al. [58,59] used atomic force microscopy to acquire the force curve from MWCNTs and small SWCNT ropes suspended across nanopores. The suspended MWCNT was considered as a doubly-clamped simple beam, and from the obtained force versus deflection data, the bending modulus was deduced to be around 1 TPa. In all of the above measurement, the Euler beam theory was simply applied to model the nanoscale mechanics of the studied CNTs, which generally have diameters above 10 nm and lengths in the order of 100 nm. The theory treated the experimental data surprisingly well. However, care must be taken for studying the mechanics of CNTs having smaller diameters, for example, SWCNT, in which the classic continuum mechanics should break down in that length scale [60].

Yu et al. [61–64] used a tensile testing tool inside a scanning electron microscope (SEM) to realize the direct measurement of the tensile mechanical properties of CNTs. The tool was developed based on a nanomanipulation stage, which allowed the picking, place and positioning of individual MWCNTs by multiple manipulation probes in free space. Atomic force microscope (AFM) probe, consisting of a force sensitive cantilever beam and a sharp tip fabricated through micromachining, was used for attaching MWCNT. The reliable attachment between MWCNT and AFM probes was realized in situ by localized electron beam induced deposition of carbonaceous materials inside SEM. A MWCNT was hold in place by two AFM probes (as shown in Fig. 2) and stretched at one end along its tensile direction by one of the AFM probes, and the force applied was measured by the deflection of the cantilever of another soft AFM probe. Stress versus strain curves were obtained (Fig. 2) and the Young’s modulus values were deduced. The obtained Young’s modulus values for MWCNT were in the range of 270 to 950 GPa [62]. In deducing the Young’s modulus value, the applied force was assumed to be sustained only by the outermost layer and the stress was calculated by assigning an effective thickness of 0.34 nm for the MWCNT layer. The assumption was made based on the observation in the experiment that MWCNT broke mostly in a “sword-in-sheath” type of fracture and the carbonaceous deposition made contact only with the outermost layer of the MWCNT. Yu et al. applied a similar method for the tensile mechanical measurement of nanoropes of SWCNT. SWCNT ropes having strong attachment at one end to the sample material were selected as candidates for the measurement [63]. In the measurement, the free end
of the SWCNT nanorope was attached to an AFM probe by nanomanipulation and in situ local deposition. The AFM probe was used to stretch the SWCNT up to the break point and the stress versus strain curves for the nanoropes were obtained (as shown in Fig. 3). The deduced Young’s modulus values from the measurements span from 320 to 1470 GPa (mean value: 1002 GPa).

Many other experimental methods have also been successfully developed and implemented for studying the elastic properties of CNTs. Raman spectroscopy was used to extract the mechanical properties of CNTs [65–70]. Lourie and Wagner used micro-Raman spectroscopy to measure the compressive stress on CNTs embedded in an epoxy matrix [65]. The Young’s modulus obtained from such measurement is 2.8–2.6 TPa for MWCNTs and 1.7–2.4 TPa for SWCNTs. Wood et al. [67] applied a similar principle to measure the temperature induced spectral shift of SWCNTs embedded in a polymer matrix. The thermal strain change of SWCNT was separated from the cohesive energy change of polymer, and the thermal strain was correlated with the frequency shift of the vibration band of SWCNT. The obtained stress-strain curve for presumably individual SWCNTs was similar to that obtained from the direct tensile measurement by Yu et al. [62]. Pan et al. [71] measured the Young’s modulus of very long (~2 mm) MWCNTs grown by chemical vapor deposition with a stress-strain puller. The average Young’s modulus value for such MWCNTs, which were more defective than the MWCNTs used by others for such measurement, was 0.45 ± 0.23 TPa, lower than those calculated and previously measured.

2.2 The Fracture Mechanism and the Tensile Strength of CNT. Based on molecular dynamics, Yokobson et al. [72] proposed a dislocation theory describing the routes of mechanical relaxation in CNT under tensile load. The formation of a specific type of dislocation consisting of a pair of pentagon-heptagon (5–7) dipole through bond rotation (the Stone-Wales transformation) was found to be the most energetically favorable for the relaxation of the CNT structure under a tensile strain of greater than 5%. The “5-7-7-5” dislocation can either separate into two “5-7” pairs gliding away along the helical path to result in a brittle fracture of the CNT under high stress, or can evolve into a crack to result in a brittle fracture (as shown in Fig. 4). The ductile transformation results in a nanotube of smaller diameter and new chiral symmetry. In general, according to Nadelli [73,74] and Yakobson [75], CNT under tension behaves as a brittle material at high strain (15 percent) and low temperature (1300 K), or as a ductile material at low strain (3 percent) and high temperature (3000 K). Samsonidze et al. [28,76] recently developed a kinetic theory to account for the effect of the rate of defect formation on the strength of CNT. The real-time strength of CNT was determined by considering the activation energies of the transition states in the Stone-Wales transformation. A yield strength in the range of 150–180 GPa for CNT was predicted. The modeling also showed an evident dependence of the strength on the chirality of CNT, different from the result obtained based on thermodynamic stability analysis in the previous studies. Dimitraca et al. [77] proposed an alternative pathway for the fracture of CNT at room temperature by the direct bond-breaking through the formation of a series of virtual defects appeared at high tension. The study found that even though the formation energy was higher for larger defects with more broken bonds, the stability range for the existence of larger defects was wider. At the state that the defect with one broken bond was formed at a high strain, the corresponding formation energy was already much higher than the energy needed for the formation of larger defects involving more broken bonds at that strain, which led to the easy transition to those defect states and resulted in a brittle fracture of CNT. Belytschko et al. [78], applying the Brenner potential combined with a modified Morse potential in their molecular dynamics modeling, recently considered the effect of defect on the strength of CNT. The result showed that, for an n-atom defect (for
The compressibility and the deformability of CNTs. Due to the anisotropic nature of the CNT structure, it is expected that the mechanical property of CNT is also anisotropic. Along the axial direction of CNT, studies have shown high rigidity and high strength, however, in the transversal direction CNT is relatively compressible and deformable.

The pattern formation for CNT under compression, bending and twisting has been modeled by various groups. Ruoff et al. [84] modeled the radial deformation between adjacent CNTs observed in TEM and pointed out the importance of van der Waals interaction in CNT mechanics. They also showed that for SWCNTs having diameters of 2.5 nm or larger to form a SWCNT rope, significant deformation could occur by van der Waals interaction between adjacent SWCNTs to result in a honeycomb cross sectional rope structure [85]. Lordi and Yao [86] simulated the deformation of CNT under a local contact or a local impact. The elasticity and resilience of the walls were found to be dependent on the tube radius and the number of layers. The result showed that even a very large force exerted on CNT produced still reversible and elastic deformation, and suggested that radial mechanical forces might not be capable of cutting a nanotube. Yakobson et al. [87] performed molecular dynamics simulation and showed the formation of different buckling patterns in CNT at the point of instabilities created with an increasing compression stress. Liu et al. [56] modeled the wavelike distortion or ripple formation along the inner arc of a bent nanotube. Their analysis indicated that there existed a critical diameter at a given load and a CNT length, for the emergence of the rippling mode. The effective bending modulus of MWCNT in mechanical resonance was shown to drop sharply as the diameter of the MWCNT increased beyond the critical diameter, in agreement with the experimental result obtained by Poncharal et al. [53]. Arroyo et al. [55] modeled the ripple formation during the bending of MWCNT, and found that the mode, similar to the Yoshimura buckling pattern, occurred only in thick-walled MWCNT, and predicted its existence also for MWCNTs subject to torsion. The effect of the ripple formation on the effective bending modulus of MWCNT in mechanical resonance was also studied in this study and a similar dependence between the bending modulus and the diameter was obtained.

Experimentally, Ruoff et al. first showed the radial deformation (partial flattening) of adjacent MWCNTs in contact observed with high-resolution TEM [84]. The deformation was the result of the van der Waals interaction between the MWCNTs. The contact pressure between the adjacent MWCNTs resulted in the slight decrease of the interlayer distance in the contact side of MWCNTs compared with that in the other exposed sides of the CNTs. Chopra et al. [88] observed a full collapsed MWCNTs in TEM and predicted the existence of such a full collapse for CNTs having a certain critical diameter and wall thickness from the energetic analysis. Benedix et al. [89] improved such an energetic model and used it to extract the interlayer interaction strength in MWCNT. The partial and full collapse of CNT on substrate surface was also observed and modeled by Hertel et al., Avouris et al., and Yu et al. [90–95]. These studies showed the importance of the CNT structure, the surface-CNT interaction and the water meniscus formation on the structural stability of CNT. Yu et al. further revealed that, from the observation of a freestanding and twisted MWCNT in TEM (as shown in Fig. 6) [95], the atomic lattice registry between the collapsed innermost layers in this MWCNT could contribute to the energetic stability of such a twisted tube, which otherwise should untwine from a simple elastic beam mechanics consideration.

Chesnokov [96] applied a quasi-hydrostatic pressure up to 3 GPa to study the volume compressibility of SWCNTs and revealed an exceptionally large and reversible volume reduction. The volume compressibility for SWCNT was measured to be 0.0277 GPa$^{-1}$. Tang et al. [97] further revealed, using synchrotron X-ray diffraction, that SWCNT was linearly elastic up to a pressure of 1.5 GPa, showed structural instability at −4 GPa and became destroyed at 5 GPa. Sharma et al. [98] reported an in situ x-ray diffraction study of SWCNT bundles under quasi-
hydrostatic pressure up to 13 GPa. Their results showed that the triangular lattice structure of the SWCNT bundles kept intact up to 10 GPa. They also showed that the reversibility of the lattice symmetry was preserved up to a pressure 13 GPa, well above the 5 GPa value observed by Tang et al. [97]. Wood et al. [66] used a diamond anvil cell with micro-Raman spectroscopy to simultaneously monitor the pressure-induced shift of various CNT bands. The study showed that the Raman peak at 1580 cm$^{-1}$ (the G band of CNT) shifted linearly with pressure up to $\sim$ 2 GPa and deviated from linearity at higher pressure. The deviation was found to be coincident with a drop in Raman intensity for the disorder-induced peak at 2610 cm$^{-1}$ (the overtone of the D* band), implying the probable occurrence of the reversible flattening of CNTs. Sandler et al. [99] investigated the pressure-induced Raman peak shifts of CNTs, graphite and carbon fiber. The CNTs and the carbon fiber displayed two distinct pressure regimes with transition pressures between 0.75 and 2.2 GPa, whereas the graphite crystals showed a linear pressure dependence up to hydrostatic pressures of 5 GPa. The observed transition in the low pressure regime was explained on the basis of geometric effects, and a reversible flattening of the CNTs was suggested at the transition pressure.

Kuzumaki et al. [54] showed a detailed examination of the bending structures of CNT using high-resolution TEM. The fine buckling structure and the reversible characteristic of such buckling ripples was revealed in the compressive side of a bent MWCNT, indicative of the flexible and resilient nature of CNT towards bending, in sharp contrast to the expected high rigidity along the length of CNT. Falvo et al. [100] demonstrated such a reversible buckling up to 42 percent of strain for MWCNT without inducing visible defects using atomic force microscopy. The quantitative measurement of the deformability of CNT by an indentation force was performed by Yu et al. and Shen et al. [101,102]. Using a new technique developed with tapping mode AFM, Yu et al. [101] was able to controllably apply indentation force on individual MWCNTs while simultaneously acquiring the AFM image (as shown in Fig. 7). The deformability of the MWCNT at any point along the whole length was revealed and the effective elastic modulus of the MWCNT for such an indentation deformation was estimated to be between 0.3 to 4 GPa. The MWCNT was found to be reversibly deformable up to a strain of 50 percent. Shen et al. [102] acquired indentation force curves from MWCNTs using contact mode AFM and estimated an effective elastic modulus of 9 to 80 GPa. The MWCNT was shown to be resilient and capable of sustaining an indentation force up to 20 $\mu$N and a deformation of 46 percent. The difference in the effective elastic modulus estimated from the two measurements could be the result of the structural difference of the MWCNTs used in the experiment, or the different methods used for the estimation of the AFM tip radius.

2.4 The Shear and Interlayer Sliding Properties of CNT.

The inherent structure of MWCNT, which consists of nested cylinders of rolled graphene sheet, provides a unique opportunity for the study of interlayer interaction between atomic perfect or nearly perfect surfaces. The interaction between the nested layers is the weak van der Waals interaction, and the spacing between the layers is $\sim$0.34 nm. It is thus expected that little resistance would be expected for the relative sliding between the nested layers, as well as the pull-out of the inner cylinders from the rest.

For the theoretical modeling of the shear and interlayer sliding in MWCNT, the classic Lennard-Jones potential is usually used for describing the interlayer atomic interaction. Kolmogorov and Crespi [103] recently developed a registry dependent graphitic potential to account for the exponential atomic-core repulsion and the interlayer delocalization of $\pi$ orbital in addition to the normal van der Waals interaction. The difference in the interlayer binding strength due to the different interlayer atomic lattice registry in graphite was obtained. For the AA and AB stacking configurations in graphite, the binding strength difference was estimated to be 12 meV/atom. In the subsequent modeling of the interlayer sliding in double-wall CNTs, they found that for commensurate CNTs (having an interlayer lattice registry) a linear dependence of the shear resistance on the contact length was obtained, while for incommensurate CNTs (having no interlayer lattice registry) there existed no such dependence. Shear strength of a few MPa was thus predicted for commensurate CNT consisting of layers having identical wrapping angles, and a shear strength of extremely small or nonexistence for incommensurate CNT with different wrapping angles or for incommensurate CNT, respectively. Zheng et al. [104] modeled the oscillatory extrusion and retraction of inner
shells of CNT from the outer shells by considering the restoring force resulted from the excess van der Waals interaction energy during extrusion and the small interlayer sliding resistance. They predicted that the oscillation frequency of such an oscillator could be in the GHz range and brought up the prospect of its high frequency device application. A subsequent study by Guo et al. [105], however, pointed out the existence of significant energy dissipation in such an oscillation system at finite temperature, which resulted in the decay of the oscillation amplitude within a few nanoseconds in incommensurate CNT and within several tens of nanoseconds in commensurate CNT. Similar conclusion was also reached by Zhao et al. [106], where the energy transfer from the translational degrees of freedom to phonon modes was studied for double-wall CNT oscillator. They concluded that for short-length CNT oscillators (less than 3 nm) a rocking motion was responsible for significant phonon energy acquisitions; and for long-length CNT oscillators the translational energies were mainly dissipated through a wavy deformation in the outer tube undergoing radial vibrations. Frictional force between the layers in the range of $10^{-17}$ and $10^{-14}$ N/atom was estimated. Double-wall CNT as rotational bearing was also modeled by Zhang et al. [107], motivated by the recent experimental demonstration of such a bearing [110]. The simulation showed that the interlayer corrugation against rotation, so the interlayer friction coefficient, was extremely small, suggesting the possible application of double-wall CNTs as wearless bearings. The extreme operational conditions for the bearing to disintegrate were also studied. Qian et al. [108] modeled the load transfer mechanism in SWCNT rope using molecular dynamics, and identified that the surface tension and the inter-tube lattice registry as the main factors for the load transfer. The study also found that introducing twist in the SWCNT rope could significantly enhance the load transfer capability of each SWCNT in the rope. Yu et al. [64] experimentally measured the dependence of the sliding force on the contact length between the MWCNT shells, and proposed that several forces were responsible for the measured sliding resistance, such as the surface tension, the shear elastic force, and the edge effect force (Fig. 8). The shear strength was found to be 0.08 and 0.3 MPa from two separate measurements showing different sliding characteristics, namely a smooth pull out and a stick-slip type sliding (as shown in Fig. 9). The difference was explained as the result of the sliding in CNTs having different degree of interlayer commensurance. Cumings et al. [109] demonstrated using a manipulation stage inside TEM the telescoping of MWCNT and observed the spontaneous retraction of the inner shells into the outer shells upon the release from its pullout position. The interlayer static and dynamic shear strength values were estimated from the observation to be around 0.66 and 0.43 MPa, respectively. A rotational bearing using MWCNT as key element was also demonstrated recently by Fennimore et al. [111] modeled double-wall CNT of various chirality pairs of inner and outer layers, and found that the potential barrier for the relative displacement of the inner and outer layers depended significantly on the chirality difference of the pair. Mechanical motions like a bolt-nut pair or discrete rotations were suggested for special pairs of chirality in double-wall CNTs. It would be interesting that the rotational bearing could also be used to study and realize those unique operations.
3 Conclusion and Perspective

The superb mechanical properties of CNTs, evident from this review, make them ideal candidates for applications related to mechanical strengthening, mechanical energy storage and absorption, high frequency electromechanical sensing and nanoscale probe, to name just a few. With the prospect of such applications come naturally new challenges in order to solve new problems and new demands for the better understanding of their fundamental properties. For example, on the study of the basic mechanical properties of CNTs, the tensile mechanical measurement of individual SWCNTs has not been realized, the mechanics related to the twist of CNT need to be further investigated. For example, on the study of the basic mechanical properties, mechanical strengthening, mechanical energy storage and absorption and new demands for the better understanding of their fundamental properties. The effect of environment on the mechanics of CNT is still not clear, the answers to these challenges and others, some intrinsic to CNT and some broadly faced with in the study of materials at the nanoscale, will eventually pave the way toward the better understanding of mechanics at the nanoscale and the realization of novel applications resulting from the related scientific discoveries.

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